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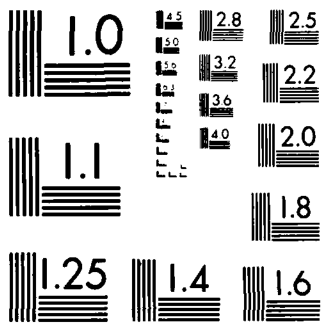

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Mapping with QUASAT Using Short Observation Times

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QUASAT (QUAsar SATellite) is the name of a proposed satellite which will be an orbiting Very Long Baseline Interferometry (VLBI) observatory. As currently conceived, QUASAT would be a joint NASA-ESA mission to fly a 15 m diameter radio antenna, with multiple frequency capability up to 22 GHz, in an orbit with a semimajor axis of about 15000 km. The two primary motivations for QUASAT are (1) to increase the maximum angular resolution from the present VLBI network by a factor of 3, and (2) to increase the dynamic range present in VLBI maps by a factor of perhaps 10. For full details on both the scientific justification for QUASAT and the presently conceived QUASAT mission, the reader is referred to the 1984 European Space Agency's publication of the proceedings of the meeting "Workshop on QUASAT, a VLBI Observatory in Space" held in Austria, 18-22 June 1984.

This report presents results of studies done to assess the imaging ability of QUASAT, with particular emphasis on QUASAT's capabilities with short observation times.

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MAPPING WITH QUASAT USING SHORT OBSERVATION TIMES

INTRODUCTION

The standard mapping scheme considered for QUASAT is a continuous 48 hour observation of each radio source. Since the orbit usually considered has a period commensurate with 48 hours (9 orbits in 48 hours), there is no additional UV-plane coverage if longer observations are used. However there are several reasons to use shorter observing times than 48 hours, such as the ability to survey more sources and the ability to observe rapid source evolution.

Ground stations obtain a full synthesis in ~ 12 hours, or roughly 2 QUASAT orbits. The rapid motion of the orbiter dominates the UV-plane coverage for the first six hours, and adds some improvement on a second orbit. Increasing the observing time to 12 hours does improve the ground-based UV-plane coverage compared to 6 hour observations, but the improvement is not by a factor of 2. Therefore, the basic unit of observing time to consider is one orbit, or about 6 hours. (Less than one orbit generally does not have the potential to fill a broad swath in the UV-plane and yields an undesirable, one dimensional fan beam.)

In order to set a lower limit on the observing time needed to map strong radio sources with QUASAT, simulations have been run to determine the fraction of time a given radio source could be adequately mapped when using 3, 6, and 12 hour observations. For the current "standard" orbital inclination, semi-major axis, and eccentricity (57 degrees, 15491 km, and 0.22, respectively) we have explored the effects on the UV-plane coverage of systematically varying the longitude of the ascending node, angle to periapsis, and the observing time. We find the following:

1. Good UV-plane coverage can be obtained for declinations near 45 degrees with either the U.S. VLB array or the European VLB Network together with appropriate stations in Europe, the USA, and Japan using observations of 6 and 12 hour duration. Three hour observations are generally not useful.

2. The penalty to be paid for 6 and 12 hour mapping is either a reduction in maximum resolution or in UV-plane sampling uniformity. The best UV-coverages for short observing times have a UV-plane sampling density similar to that seen for full 48-hour observations, but the resolution in each dimension is reduced by about 25%.

3. The uniformity of the UV-plane sampling for a given observing time may be substantially improved if the direction to the radio source is ~ 30 to 60 degrees away from the perpendicular to the orbit (that is, the "viewing angle" is 30 to 60 degrees).

4. For observations at declination 45 degrees, either the U.S. VLB array or the European VLB array could be used in a 6 or 12 hour observing mode, based on the sampling of the UV-plane which can be achieved.

5. For sources near the equator, the U.S. VLB array can yield adequate coverage with 6 hour observations. While the sampling for sources

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near the equator is not as good as at higher declinations, the enhancement of the low declination UV-coverage over the ground stations alone is quite large. Map quality for low declination sources is often limited by either ground array coverage or by telemetry limitations.

6. Excellent UV-coverage for 2 degrees declination can be obtained in 12 hours using the U.S. VLBA plus two additional telescopes when the viewing angle is ~ 45 to 60 degrees.

7. In mapping variable or flaring sources, good coverage is obtained in 6 hour observations about 60% of the time for sources at 45 degrees when using a global VLB network. For sources near the equator good maps can be obtained when the source is visible from both the U.S. and Europe about 40% of the time.

8. A fourth telemetry station (Malindi) plays an important role in improving the UV-coverage for short duration observations. A fifth telemetry station may be useful.

SIMULATIONS WITH 32 GROUND STATIONS

In an effort to determine the usefulness of QUASAT for mapping radio sources using only brief observations, we have examined a sampling of the orbital geometries for their resulting UV-plane coverages. The different orbits we examined simulated the effects of precession and different source right ascensions on the UV-plane coverage, for a particular orbit. Holding the orbital inclination to 57 degrees, the semi-major axis to 15,549,140 m, and the orbital eccentricity to 0.22, we varied both the angle to periapsis and the longitude of the ascending node in steps of 60 degrees, and the observation time in steps of 6 hours. We did not vary the mean anomaly or the source right ascension, but the angle to periapsis and the longitude of the ascending node were both varied through a complete 360 degrees. Our sampling of the orbital geometry therefore includes the effects of orbital precession and source right ascension, and allows us to determine the probability of good UV-plane coverage being available for a radio source.

Initially, in order to minimize the effects of the ground stations on the orbital UV-plane coverage for each set of orbital and time parameters, we selected a global VLBI array with the largest possible number of stations (a total of 32 ground stations; see Table 1). These stations represent all stations which could have 22 GHz VLBI capability at the time QUASAT is flown. This is almost certainly unrealistic for any experiment, but does allow us to comment on the number of stations needed for effective mapping in 6 hours.

This initial sampling of the orbital parameters produced 144 different examples of the UV-plane coverage for a single declination; we examined two different declinations (45 degrees and 2 degrees) to determine how the coverage degraded at low declinations. We assumed that there would be four telemetry stations available for QUASAT, having included the ESA Malindi telemetry station in addition to the three DSN antennas in the Readhead *et al.*'s report.

The UV diagrams we produced were examined qualitatively and classified as having "good", "medium", or "poor" UV-plane coverage, relative to the others

TABLE 1

Antenna Elements in Simulated Global Array

Other European	Other Australian	VLBA	N. America	Global
Cambridge	Coon	Arecibo	Algonquin	
Itapatinga				
Crimea	Narrabri	Bernal	Goldstone	Madrid
Effelsberg	Parkes	Fort Davis	Green Bank	Nobeyama
Jodrell Bank	Tidbinbilla	Haystack	Md. Point	
Noto		Iowa	Rosewell	
Medicina		Kitt Peak	VLA	
Onsala		Maui	VLA E3	
		Oroville	VLA E4	
		Owens Valley		
		VLA E5		

at the same declination. "Good" UV-plane coverage is defined as sampling which, at 22 GHz, satisfies the following criteria:

1. Maximum UV distance greater than $\sim$ 1.4 billion wavelengths (about twice the maximum Earth-based baseline).

2. No holes in the UV coverage larger than $\sim$ 0.2 billion wavelengths.

3. Ratio of the *maximum* UV distance to the "minor axis" of the UV coverage of less than 2:1.

"Medium" UV coverage violated criterion both (1) or (2) above, but would still produce an acceptable beam. "Poor" UV-plane coverage is defined as sampling which violates at least criteria (3) or both (1) and (2). Even when QUASAT produced "Poor" sampling, a reasonable map with substantial improvement in resolution over ground-based VLBI could still be produced, although the map might have a relatively low dynamic range.

For the simulations at declination 45 degrees involving 32 stations, 12% fit the good category, 42% fit the medium category, and 47% were poor. The percentages are the same for declinations 45 and 2 degrees if the second criteria is relaxed to allow holes of $\sim$ 0.3 billion wavelengths.

Figures 1, 2, and 3 show results from our simulations of QUASAT plus 32 ground stations for declinations 45 and 2 degrees. Figures 1, 2, and 3 show typical examples from the good, the medium, and the poor categories, respectively.

Based on this first set of simulations, we suggest that for high declination sources, effective 6-hour observations could involve either Europe plus North American stations or the U.S. VLBA plus an outrigger station in Europe and (possibly) Japan. The combination of VLBA plus a few European outrigger stations provided most of the UV sampling for the times when the VLBA was

visible to the source, with only minor contributions to the UV coverage coming from baselines involving other stations (such as Australia). Thus, about 12 stations in the U.S. and Europe provide most of the useful coverage for 6 hour observations. An array with a greater number of stations is not necessary for mapping high declination sources, unless improved sensitivity is needed or the source has extremely complex structure.

In contrast, at low declinations the only times when reasonable UV-plane sampling was obtained was when the radio source under study was visible from the VLBA and QUASAT. Stations in Europe, Japan, and Australia add relatively little to the UV-plane coverage for low declination sources, under the conditions we used, for two primary reasons. First, the European stations are generally much further north than the U.S. VLBA, resulting in reduced UV-plane coverage. Second, the Australian stations are both too close together and too isolated from other stations to do much more than fill in a small area of the UV-plane. However, a single Australian or European station is useful for observing low declination sources in certain circumstances, depending on the orbital geometry.

SIMULATIONS WITH SMALLER ARRAYS

It was apparent from the 32 station simulations that UV-coverage almost as good as that from 32 ground stations could be obtained with much smaller arrays, if the smaller arrays had a very broad geographical distribution of antennas. Even though reducing the number of stations reduces the density of the UV-plane sampling, the large unsampled areas (holes) in the UV-plane coverage left by a 12 to 14 station array were neither much larger nor much more numerous than those left by a 32 station array. We therefore ran simulations with two different arrays:

1. An 11-station European-based array consisting of the European VLBI Network plus three stations in the U.S. plus one in Japan (see Table 2); and

2. A 12-station U.S.-based array consisting of the U.S. VLBA plus one European and one Japanese station (see Table 3).

TABLE 2

Antenna Elements in Enhanced EVN Array

European	Australian	VLBA	Other N. America	Other Global
Crimea		Haystack	Green Bank	Nobeyama
Effelsberg		Owens Valley		
Jodrell Bank				
Noto				
Medicina				
Onsala				
Westerbork				

TABLE 3

Antenna Elements in Enhanced U.S. VLB Array

European	Australian	VLBA	Other N. America	Other Global
Effelsberg		Arecibo Bernal Fort Davis Haystack Iowa Kitt Peak Maui Oroville Owens Valley VLA E5		Nobeyama

These simulations were run at declinations of 45 and 2 degrees, for observations lasting both 6 and 12 hours (the mean observing time was selected to give good UV-plane coverage from the ground-based array). In order to adequately sample the possible orbit geometries, we varied both the angle to the ascending node and the longitude of periapsis through 360 degrees in 60 degree steps, and allowed the mean anomaly to assume values of 0 and 180 degrees.

The actual percentages achieved by each array at each declination for each observing time in each category ("good", "medium", or "poor") are listed in Table 4.

(a) The U.S.-Based Array

The U.S. array performed well at both 2 and 45 degrees declination with both 6 and 12 hour observations. Figure 5 is representative of the best UV-plane coverage which we achieved using the U.S.-based array, for observations of 6 and 12 hours duration, at both 2 and 45 degrees declination. In the low declination, 12-hour case, QUASAT has dramatically improved the UV coverage. The evenness of the UV sampling is partly a result of the fact that the viewing angle to the source (the angle between the orbital plane and the direction to the source) was about 45 degrees. This uniformity comes at the expense of a slight loss of resolution, and a slightly elliptical beam shape.

Figure 5 clearly demonstrates the ability of QUASAT to provide excellent low-declination UV-plane coverage when a suitable viewing angle is used. If a viewing angle of zero had been used, large holes in the UV-plane coverage would be opened up to the north and south of the coverage from the ground-based array.

TABLE 4

Ratings of UV-plane Coverage for Simulated Arrays

Network	Declination	Observing Time	"Good"	"Medium"	"Bad"
Global	2 degrees	6 hours	12 %	42 %	47 %
	45	6	12	42	47
EVN +	2	6	2	72	26
		12	1	92	7
	45	6	0	56	44
		12	4	47	49
VLBA +	2	6	14	72	14
		12	32	67	1
	45	6	6	52	42
		12	21	49	28

(b) The European-Based Array

The European-based array we tested did not perform as well as the enhanced U.S. VLBA in simulations involving 2 degrees declination and short observing times (either 6 hours or 12 hours). At declination 45 degrees, however, the performance with 12 hour observations was reasonable, yielding "good" or "medium" quality UV-plane sampling for $\sim$ 50% of the simulated observing geometries. Figure 4 is representative of the best UV-plane coverage which we achieved using the European-based array we selected, for observations of 6 and 12 hours duration, at both 2 and 45 degrees declination. Using the classification scheme discussed in section II, the UV-plane coverages in figure 4 would be rated "good" or, in the case of the 6 hour low-declination observation, "medium". However, when comparing these results to those for the U.S. based array below, it must be kept in mind that we have not tried to find optimum outrigger stations for the European Network. It is likely that a significant improvement in the fraction of the time which the European network yielded "good" UV coverage for short observations could be achieved with a carefully selected new antenna.

IMPROVED TELEMETRY

During all times when the ground array is observing the source there must be telemetry coverage to the satellite. Presently, at least three DSN stations are under consideration as possible telemetry stations: Spain,

Goldstone, and Tidbinbilla. A fourth ESA tracking station in Malindi has been suggested to help observations with the European VLBI Network (it also helps observations with the U.S. array). All four of these telemetry stations are within 7 degrees of a single great circle. Near the poles of this great circle are regions where little or no telemetry is available (see Figures 6 and 7).

Since the Japanese deep-space tracking station in Kashima, Japan is near one of the poles, we chose to study the effect of adding Kashima to the telemetry array. For comparison, we also studied the effect of dropping Malindi to form a three-station telemetry array. We ran simulations at 2 degrees declination for the VLBA + Bonn + Nobeyama (we expect that the results would be similar for the European-based array) with the 3, 4, and 5 station telemetry arrays. Only a 6 hour observing time was considered, for a set of 36 simulations covering both the angle to the ascending node and the longitude to periapsis in 60 degree steps. We find that, compared to the 3 station telemetry, the UV-plane coverage was typically improved by $\sim$ 25% by the addition of Malindi and frequently by $\sim$ 50% when both Malindi and Kashima were included as telemetry stations. In some cases the 5 telemetry stations provide even more improvement, as shown in Figure 8. The UV-coverage is improved from "poor" to "medium".

The ESA tracking station in Kourou (French Guyana) is also in a good location for improving the telemetry coverage, but we have not tested its effect.

CONCLUSIONS

Our main result is that high quality UV-plane coverage can be obtained from QUASAT with observing times as short as 6 hours. Furthermore, the fraction of time for which the UV-plane sampling is good is significant. When the viewing angle to the radio source is very small, (that is, the direction to the source makes a small angle to the plane of the orbit) poor UV-plane coverage results, although occasionally reasonable coverage can still be obtained for such sources.

We have also discovered an important method to eliminate holes in the orbiter-to-ground UV-plane coverage. Undesirable holes can almost certainly be eliminated by using a suitable non-zero viewing angle. This has relevance to observations of any duration. In particular, some of the uneveness seen in 48-hour observations with QUASAT and the European network could probably be decreased easily in this way. The tradeoff is that circularity of the synthesized beam is traded for uniformity of coverage.

The penalty to be paid for 6 and 12 hour mapping with QUASAT is either a loss of resolution or a loss of the uniformity of the sampling of the UV-plane. The best coverages we have found have a sampling density of the UV-plane similar to that seen for full 48-hour observations, but the resolution in each dimension is reduced by about 25%, or about $\sim$ 50% in total area.

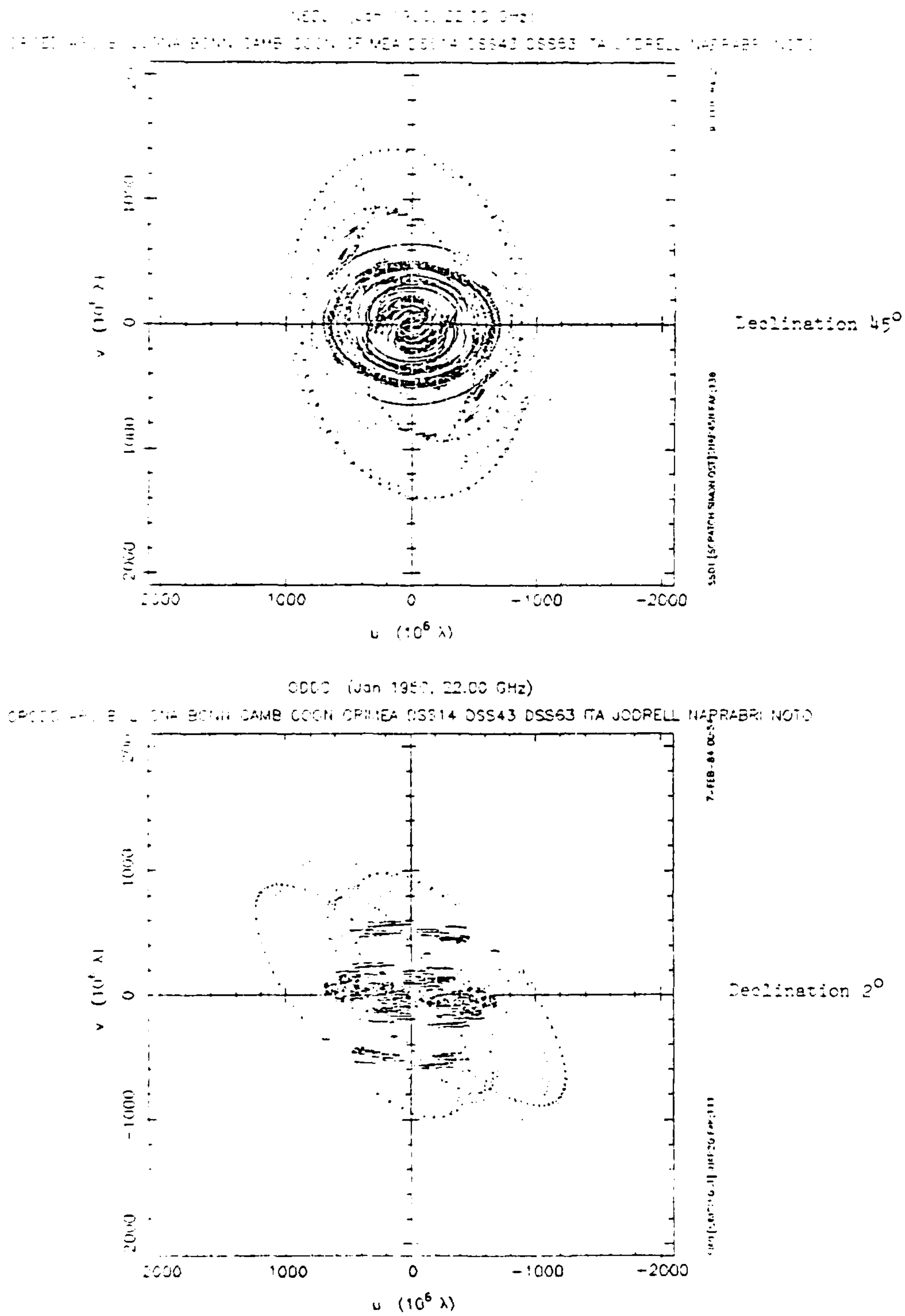


Figure 1. Examples of "good" UV-plane coverage using a global (32-station) VLB array and 4 telemetry station for a 6 hour observation. 22 GHz was the assumed observing wavelength; the axes are labeled in millions of wavelengths. The upper figure is for declination +45 degrees; the lower figure is for declination 2 degrees.

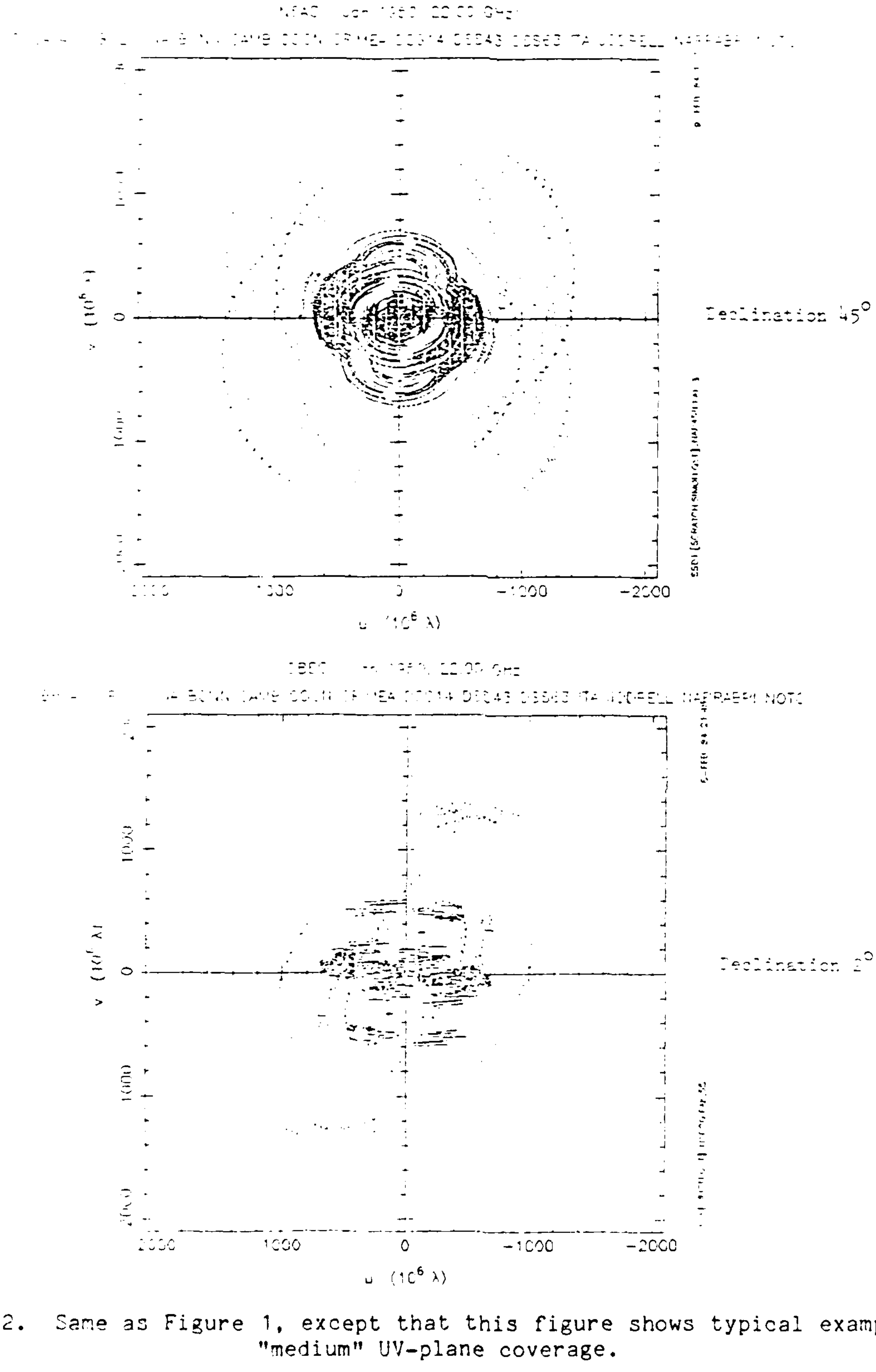
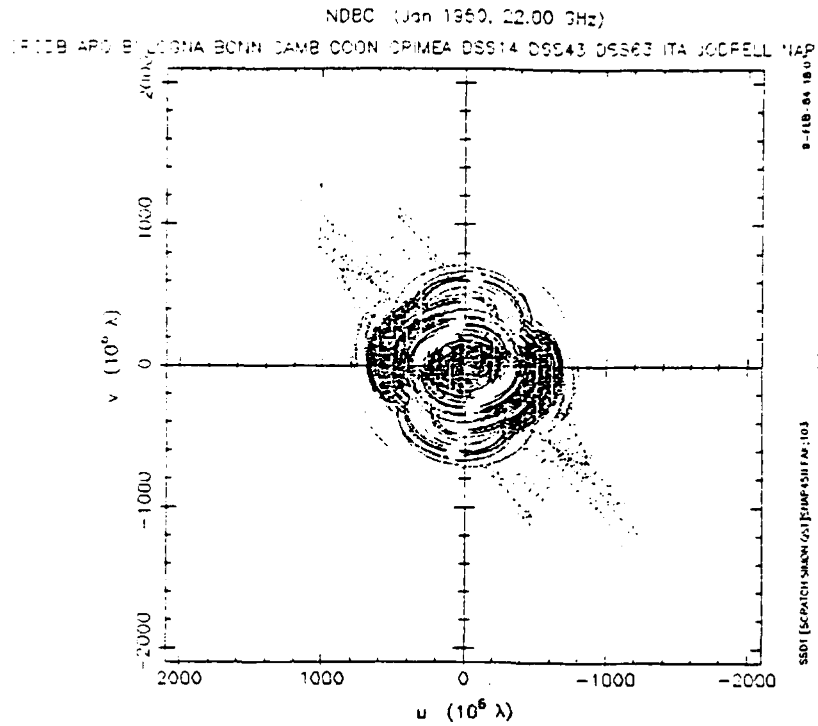


Figure 2. Same as Figure 1, except that this figure shows typical examples of "medium" UV-plane coverage.



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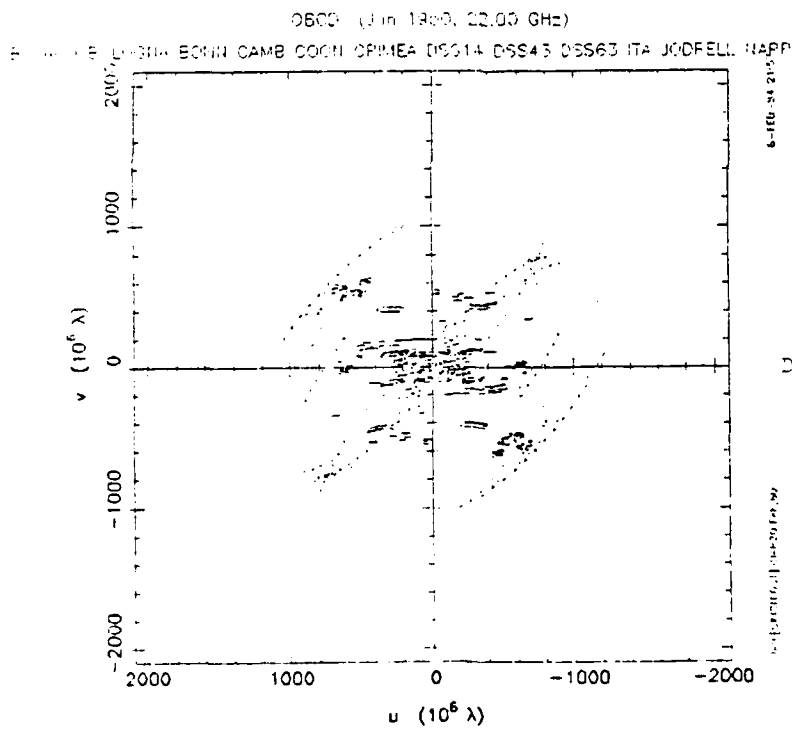

Declination 2°

Figure 3. Same as Figure 1, except that this figure shows examples of "poor" UV-plane coverage.

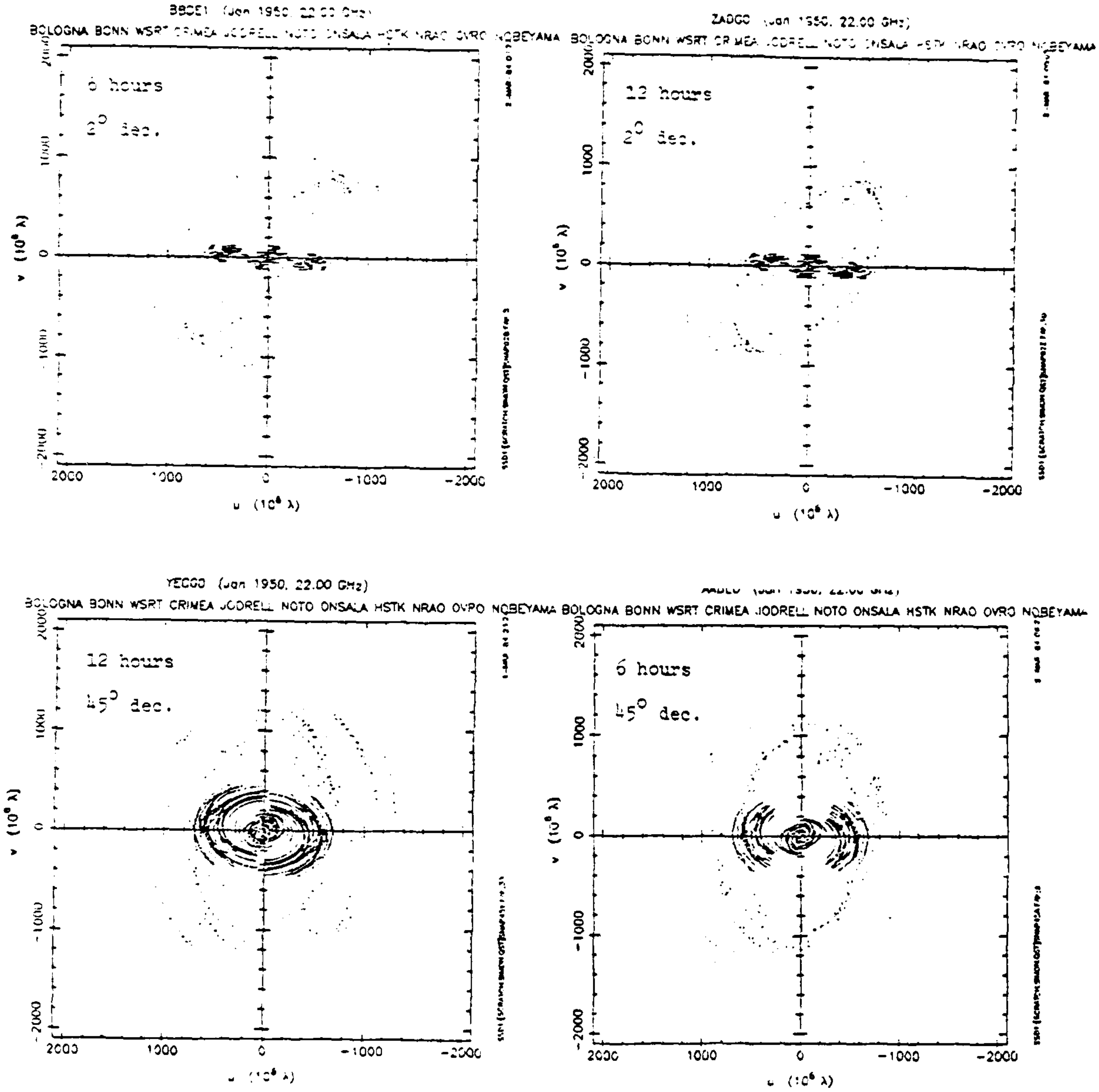

Figure 4. Examples of UV-plane coverage using the European-based VLB array. The UV sampling shown here represents either 6 or 12 hours of observation of a source at either 2 or 45 degrees declination.

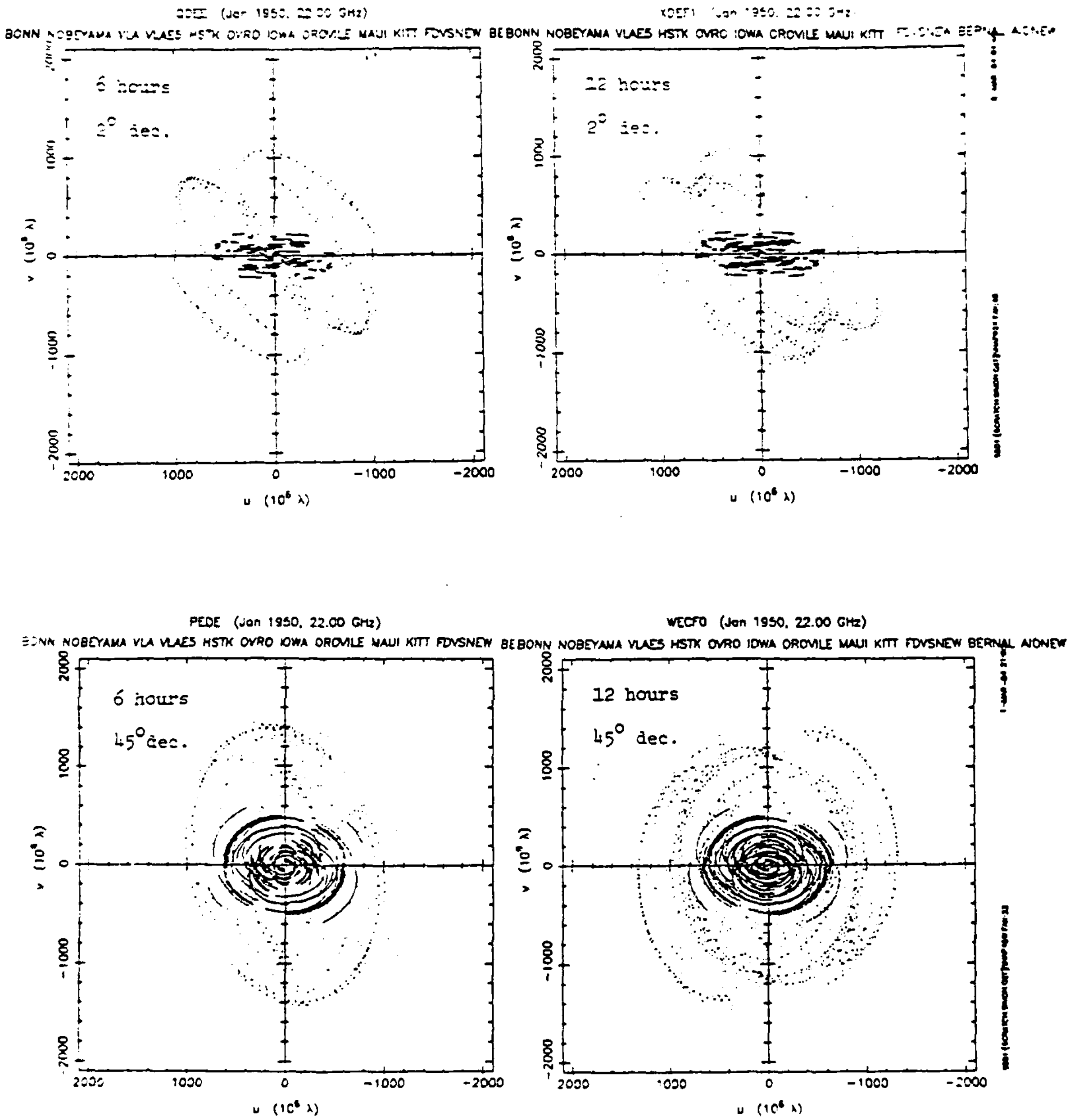

Figure 5. Examples of UV-plane coverage using the U.S.-based VLB array. The UV sampling shown here represents either 6 or 12 hours of observation of a source at either 2 or 45 degrees declination; all examples in this figure would be rated "good".

Figure 6. An orthographic projection of the Earth showing the hemisphere in which the 4 telemetry stations we used for most of our simulations are located. The 4 telemetry stations are located very near the edge of the projection; their approximate locations are marked with a circled asterisk.

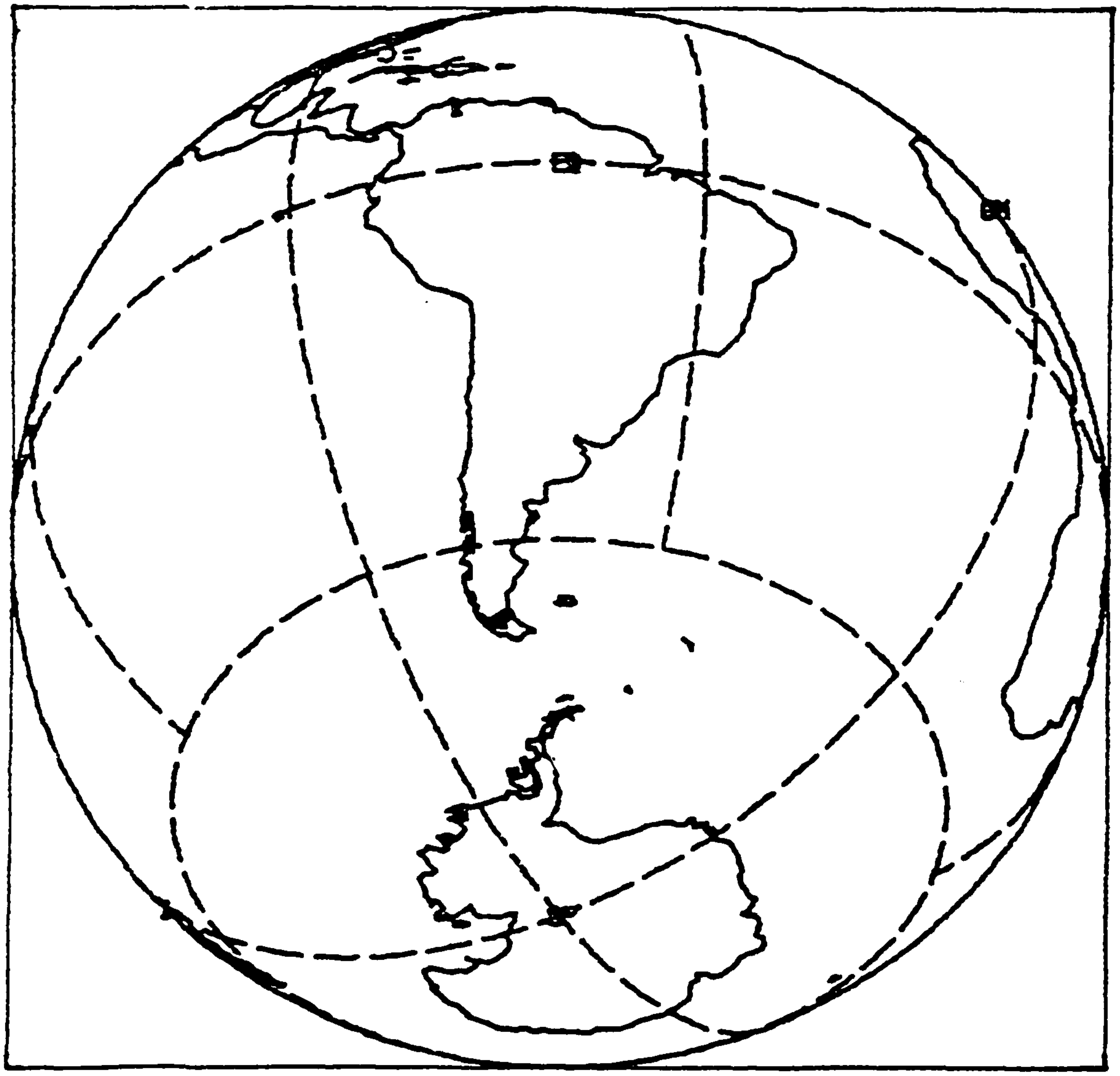

Figure 7. The hemisphere opposite that shown in Figure 7. Of the four telemetry stations used for most of our simulations, none is visible.

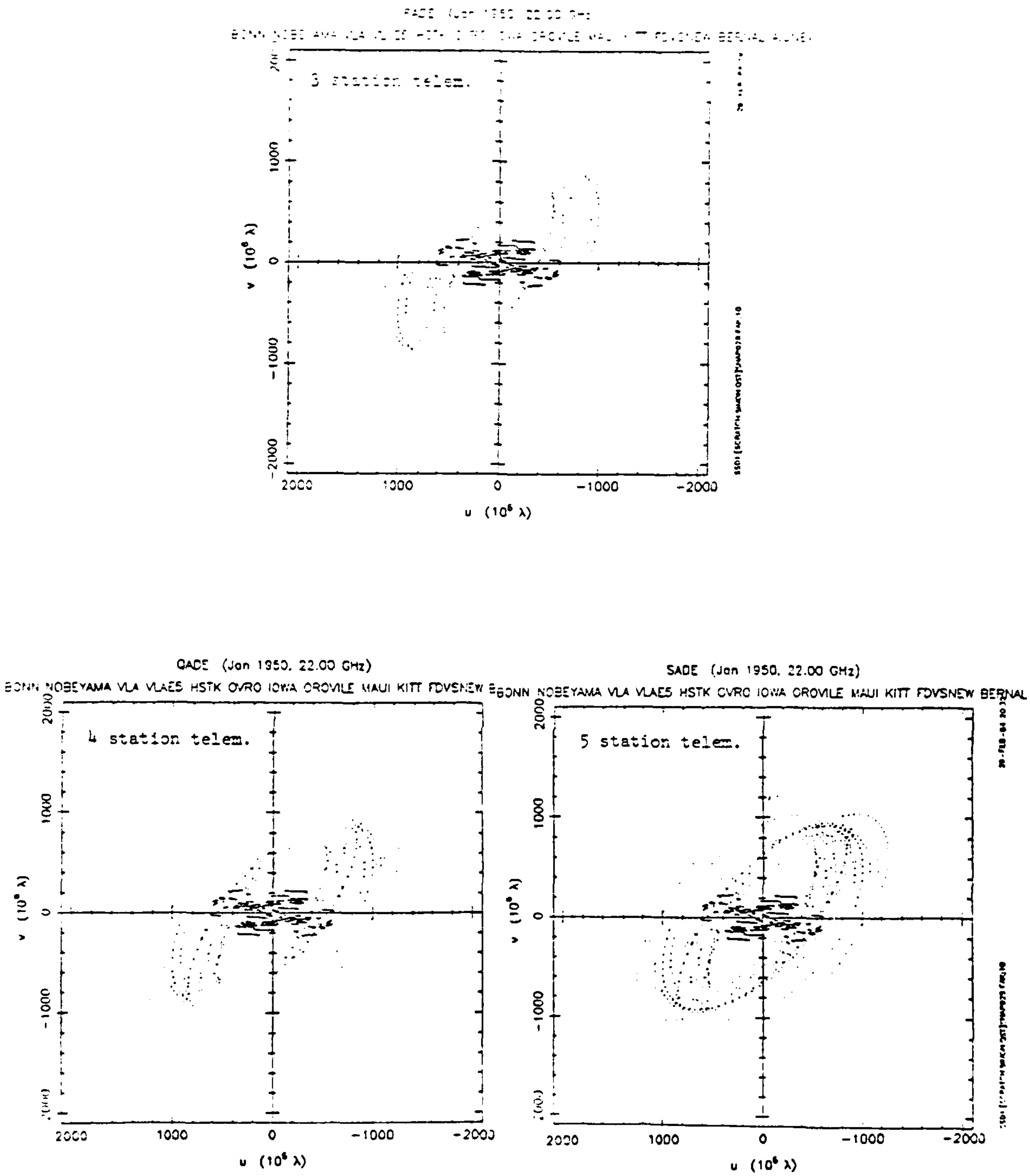

Figure 8. An example of the improvement which can be achieved as the number of telemetry stations is increased from 3 (Goldstone, Madrid, and Tidbinbilla) to 4 (adding Malindi) to 5 (adding Kashima).

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